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Research Article

An Investigation of Factors Influencing Bear Spray Performance

TOM S. SMITH,[1] *Brigham Young University, 701 East Campus Parkway, Provo, UT 84602, USA*
JAMES M. WILDER,[2] *U.S. Fish and Wildlife Service, Marine Mammals Management, 1011 E. Tudor Road, Anchorage, AK 99503, USA*
GEOFFREY YORK, *Polar Bears International, 810 North Wallace, Unit E, Bozeman, MT 59715, USA*
MARTYN E. OBBARD, *Ontario Ministry of Natural Resources, Trent University, Peterborough, ON K9J 7B8, Canada*
BLAKE W. BILLINGS, *Chemical Engineering Department, University of Utah, Salt Lake City, UT 84112, USA*

ABSTRACT Several studies have documented the effectiveness of bear spray in protecting users from aggressive bears. Bear spray failures, however, have also been reported along with speculation regarding the influences of temperature, wind, repeated canister use, and canister age on spray efficacy. We designed lab and field experiments to document the influence that temperature, wind, repeated discharges from the same canister, and canister age have on bear spray performance. To determine the influence of temperature on spray performance, we recorded canister head pressures at temperatures ranging from −23°C to 25°C and found a strong, positive linear relationship. Even at the lowest temperature tested (−23°C), bear spray had a range >4 m, though the plume was narrow and the spray was not well aerosolized. As canister temperature increased, head pressure, plume distance, and dispersion increased. We used computational fluid dynamics modeling and simulated the effect that headwinds, crosswinds, and tailwinds of varying speeds had on spray performance. Even under high headwind and crosswind scenarios (>10 m/sec), sprays reached targets that were approximately 2 m directly in front of the user. Crosswinds affected spray plume distance similar to headwinds, but the effect was not as pronounced. Tailwinds improved spray performance with respect to speed and distance. By weighing unused canisters ≤18 years old, brands tested lost weight ranging from 0.65 g/year to 1.92 g/year, presumably because of propellant that escaped canister seals. We also documented that bear spray head pressure declines in a logarithmic, not linear, fashion; over half of a new (7-sec spray time) canister's pressure was lost in the first 1 second of spray. We recommend not test-firing cans, keeping cans warm when in the cold, and retiring them when ≥4 years of age. Our results provide no compelling reason to not carry bear spray in all areas where bears occur, even if it is windy or cold.

KEY WORDS bears, bear attack, bear behavior, bear deterrents, bear spray, human-bear conflicts.

We can contribute to bear conservation by reducing bear mortalities due to human-bear conflicts. To adequately protect people living, recreating, and working in bear country, wildlife professionals and the public need non-lethal tools to use against aggressive bears. Bear spray is an effective non-lethal deterrent when dealing with brown (*Ursus arctos*), black (*Ursus americanus*), and polar bears (*Ursus maritimus*; Herrero and Higgins 1998, Smith et al. 2008). Concern regarding the ability of bear spray to protect users in windy or cold conditions, however, contributes to a reluctance to rely upon it for protection, particularly in northern regions where these conditions prevail (Herrero and Higgins 1998, Smith et al. 2008).

Bear spray has 3 components: oleoresin capsicum (OC), a carrier or thinning agent, and a propellant (Reimers 2016). Oleoresin capsicum is a viscous, oily substance that contains 1–2% capsaicin and related capsaicinoids, the active ingredients in bear spray that elicit intense burning sensations, involuntary blepharospasms, and restriction of airways (Herrero and Higgins 1998, Miller 2001). It is this chemical effect on a bear's senses that makes the product effective as a deterrent (Rogers 1984, Herrero and Higgins 1998, Smith et al. 2008). Because OC is an oil-based, syrupy substance, it must be thinned so it disperses into small droplets when discharged from the bear spray canister. Consequently, a thinning agent is added and these agents are proprietary and reportedly vary by manufacturer (Reimers 2016). At the time of this research (2017–2019) the propellant used for all bear spray products was a refrigerant (R134a; Dupont, Wilmington, DE, USA) that boils at −26.1°C (Dupont 2020). The United States Environmental Protection Agency (2019) recently proposed that industry phase out all uses of R134a and substitute a propellant with

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[1]*E-mail: tom_smith@byu.edu*
[2]*Current affiliation: U.S. Forest Service, Bridger-Teton National Forest, 340 North Cache, Jackson, WY 83001, USA*

a much lower global warming potential, 1234ze (Honeywell International, Morris Plains, NJ, USA; Honeywell 2020). Of bear spray products, Counter Assault™ (Counter Assault, Kalispell, MT, USA) is the only one that adopted using 1234ze in 2019. Honeywell (2020) claims that 1234ze performs similarly to R134a.

Our research objective was to document the effects that temperature, wind, repeated bursts (i.e., short releases of spray) from the same can, and time (i.e., expiration date) have on bear spray performance. We did not compare performance of the various bear spray products under a variety of environmental conditions. We assumed wind, temperature, repeated bursts, and time effects on spray performance broadly apply to bear spray products regardless of manufacturer.

STUDY AREA

We performed this work on the campus of Brigham Young University, Provo, Utah, USA. The campus is located at the base of the Wasatch Mountains (40.2518°N, 111.6493°W) at an elevation of 1,411 m. We conducted laboratory and outside experiments on the 2.3-km^2 campus.

METHODS

Canister Temperature

To eliminate the risk of exposure to bear spray within the research lab at Brigham Young University, we used inert bear spray cans (260 g; UDAP, Butte, MT, USA) for testing the effect of temperature on canister head pressure. Inert test cans are sold solely for the purpose of practicing bear spray deployment without risk of exposure to the active ingredient (capsaicin), and are reported to perform similar to actual bear spray because both use the same propellant (UDAP 2020). We removed the nozzle and trigger assembly from test cans as described by Gookin et al. (2014), and inserted a modified nozzle with plastic tubing attached (Fig. 1). When we depressed the trigger, the pressure released into the tubing was displayed on a digital pressure gauge in kilopascals. This nozzle modification allowed us to accurately measure canister head pressure with a minimal loss of content (<1% per trigger). After each pressurization of the tubing and gauge, we released the gas under a vented hood in the lab, then continued with the next pressurization until the test was completed. This procedure allowed us to construct a record of how bear spray pressure varied as a function of can temperature and how repeated bursts of spray individually and cumulatively affected canister pressure.

To document the effect of temperature on spray performance, we chilled cans in an ultra-low freezer (VWR International 2020) to −50°C then allowed them to slowly warm to the target temperature for testing. Prior to freezing, we taped a type K thermocouple (REOTEMP Instrument Corporation, San Diego, CA, USA) to each canister to relay temperature back to a digital thermometer. A type K thermocouple is widely used in lab testing because it is inexpensive, accurate, reliable, and has a wide temperature range (REOTEMP 2020). Once removed from the freezer, we inserted the modified nozzle, replaced the firing trigger and

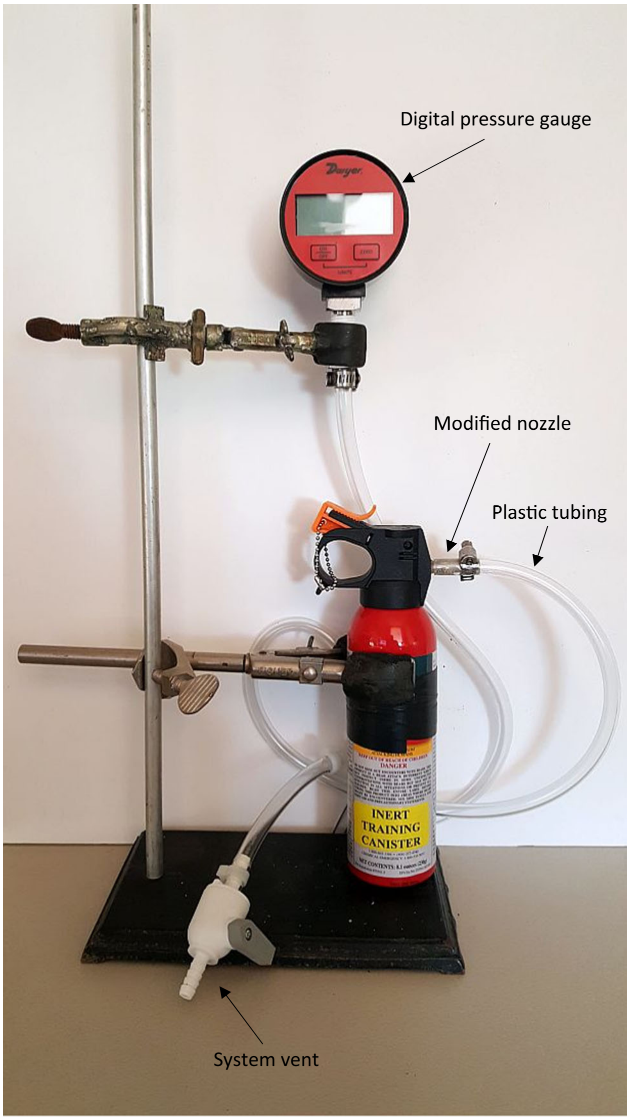

Figure 1. Bear spray connected to digital meter for head pressure measurement.

attached the digital pressure gauge and digital thermometer (Fluke 52-II Dual Input Digital Thermometer; Fluke, Everett, WA, USA). Once the can reached the target temperature, we recorded the head pressure in kilopascals at each of the following temperatures: −40, −30, −20, −10, 0, 10, and 20°C. Because very little product is used to pressurize the system, we recorded 1 series ($n = 7$) of pressure measurements from each inert can.

To document the relationship between canister temperature and associated bear spray plume (distance and dispersion), we refrigerated cans of actual bear spray product (Counter Assault™ 260 g), not inert practice cans. We chilled bear spray canisters to −40°C in an ultra-low freezer, as indicated by a type K thermocouple sensor attached to the digital thermometer. We placed chilled cans of bear spray into an insulated cooler to retard heat loss then drove to a location 2 km north of the Brigham Young University campus to minimize the chance of people interacting with diffusing bear spray. At the test site we laid down a 112-cm-wide by 12-m-long roll of white paper on the ground. We positioned a bear spray canister atop of a camera tripod so the spray nozzle measured 50 cm above the ground (Fig. 2). We used a wind meter (Kestrel™ 1000; Kestrel, Boothwyn, PA, USA) to verify the absence of a breeze, and depressed the trigger for 2 seconds. We used a tape measure to record the resulting orange-red spray pattern at 3 distances: to the farthest reach of red droplets on the paper (100% of spray plume), to the terminus of the greatest concentration (95% of spray plume), and to the center of the most concentrated pattern (90% spray plume). We repeated this procedure for the same temperature ranges used for testing head pressures (−40, −30, −20, −10, 0, 10, and 20°C).

Wind

To determine how wind affects bear spray performance, we ruled out using actual spray cans because of the inability to control wind velocities and accurately quantify results (e.g., distances bear spray plumes reached under a variety of wind speeds and directions). To address these challenges, we turned to computer simulation software (Flame Dynamics Simulator) that uses a National Institute of Standards and Technology computational fluid dynamics program. To run computational fluid dynamics simulations, we had to know the velocities of actual bear spray droplets exiting the nozzle over time and distance. To determine those values, we used a high-speed camera (Sony RX100iv; Sony, Wuxi, China; 960 frames/sec) to document the distance traveled per unit time by the bear spray plume. We taped to a concrete retaining wall a 112-cm-wide by 12-m-long roll of white paper that was gridded with 1-cm × 1-cm squares, with each meter marked with a heavy black line so we could interpret plume distances (cm) versus time accurately in the photographic record (Fig. 3). We imported video sequences into Adobe Premiere Pro™ (Adobe, San Jose, CA, USA) video editing software for frame-by-frame analysis to determine bear spray plume distance versus time so that we could calculate velocities. We used averaged velocity data derived from 8 trials in our wind simulation modeling as our measure of velocity.

We set the initial velocity of simulated bear spray droplets in Flame Dynamics Simulator to match the velocity of actual droplets from the high-speed photography. We visualized distance of travel of the spray using an image slice taken from down the center of the simulation area that measured the spray mass fraction (Fig. 4). We selected a nozzle setting in Flame Dynamics Simulator that simulated spray as it exits a bear spray canister. The nozzle was positioned in the center of the $x = 0$ face and oriented to spray perpendicular to the face. We propagated winds in the simulation at each of the x faces for the simulations of spraying into the wind and with the wind, and at each of the y faces for spraying into a crosswind.

We ran the simulation for 120 seconds. The first 60 seconds were to let the wind from the x faces propagate through the entire simulation area. The nozzle then began to spray at 60 seconds for 60 seconds to observe the spray. We exported these 60 seconds of simulation as video frames and analyzed them using MATLAB (MathWorks, Natick, MA, USA) image processing to find the distance

Figure 2. Field testing of bear spray distance and dispersion as a function of canister temperature. Bear spray was placed atop the tripod in the foreground, putting the nozzle at 50 cm above the ground.

Figure 3. Setup for documenting bear spray velocities, distance, and time. High-speed camera in foreground recorded 960 frames/second, allowing the calculation of velocity from recorded distance and time for spray.

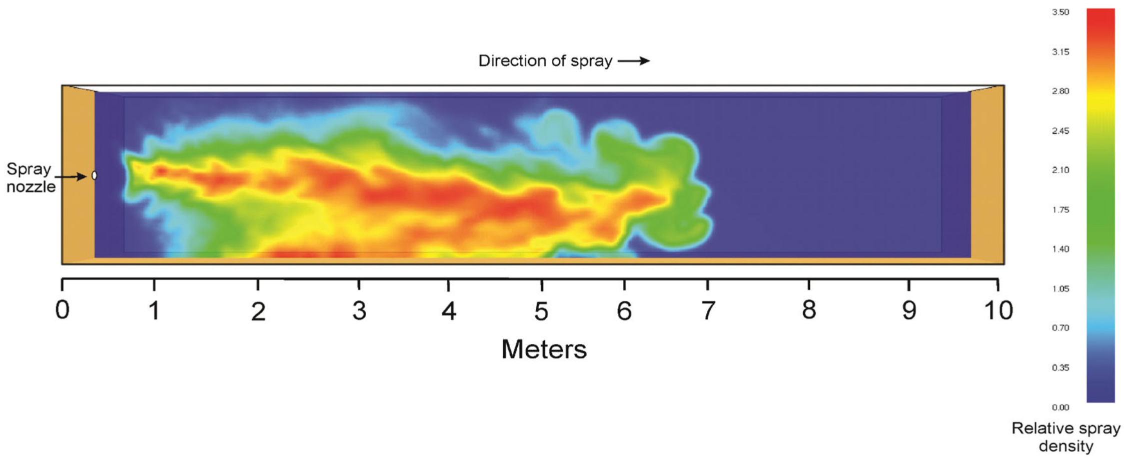

Figure 4. Bear spray plume simulation for the base case of no wind. The colored area indicates the spray plume's density and dispersion at time = 70 seconds post triggering.

from the nozzle reached by the spray. We measured the distance directly in front of the nozzle in the *x* direction.

We ran simulations at baseline (no wind) and at 11 wind velocities each for headwinds, tailwinds, and crosswinds. Velocities (m/sec) used in simulations included 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 m/second. We calculated and normalized the average and maximum spray distances under each wind scenario (direction and velocity) using MATLAB.

Repeated Releases

To investigate the effect that multiple releases (bursts) of spray contents from the same can had on bear spray performance, as measured by head pressure, we connected cans of inert and actual product to the pressure testing apparatus (Fig. 1). Once connected, we depressed the trigger to pressurize the system, then recorded the trigger number (1 to *n*) and associated head pressure. We then released pressure in the tubing and the repeated the process until the can was empty (pressure = 0 kilopascals).

Time

The propellant (R134a) used in bear spray canisters escapes past canister seals over time (T. Lynch, UDAP Industries, personal communication). By weighing and pressure-testing unused bear spray cans of known age (as determined by expiration dates on cans), we were able to determine the rate of loss of propellant as a function of canister age. All expired bear spray canisters were provided by the United States Department of Agriculture Shoshone National Forest, Cody, Wyoming, USA.

To determine if a canister had never been used, we probed the nozzle with a white cotton swab dipped in rubbing alcohol. If orange residue appeared on the cotton swab, we eliminated those canisters from this test. We weighed all unused canisters and recorded their weight (g) along with its age (in yrs) to estimate loss of propellant over time. We also recorded the head pressures of all unused canisters following the same procedure used for assessing the effects of temperature on head pressure. We plotted these data in weight, pressure, time curves using the linear regression function in Excel (Microsoft Corporation, Redmond, WA, USA) to generate predictive models of propellant and pressure losses over time.

RESULTS

Canister Temperature

Head pressure was positively correlated with canister temperature ($R^2 = 0.9572$; Fig. 5). The linear regression of these data shows that for every degree of temperature increase, head pressure would be expected to increase by 7.1 kilopascals. This regression equation also predicted that at −163°C, a can of bear spray has essentially no pressure.

We documented the relationship between head pressure and spray performance using actual bear spray product (oleoresin capsicum present) on windless days (Fig. 6). Distances were correlated ($R^2 = 0.88$) with canister temperatures, as anticipated. As determined from linear regression, when bear spray is chilled to −54°C, it will not spray. Bear sprayed at −23°C, −17°C, and 18°C extended >4 m, but the sub-zero plume dispersed considerably less than those from warmer cans (Fig. 7). We did not measure plume dispersion because at temperatures above freezing, no discernible margins were visible.

Wind

We photographed 8 trials of bear spray being emptied in front of a grid using high-speed photography (Fig. 3). Based on these 8 trials, the speed at which bear spray moved forward exponentially declined in the first 0.3 seconds (from 19.5 m/sec to 3.0 m/sec) then leveled off at approximately 3.0 m/second for the first 1.5 seconds of spray; the spray plume transited 8 m in 3.2 seconds, for an average speed of 2.5 m/second (Fig. 8).

Analysis of each of the wind direction simulations (headwind, crosswind, and tailwind) showed that the wind does not completely negate the reach of the bear spray (Fig. 9). Specifically, with a headwind, plume distance is quickly reduced to about 1.5–2.0 m but held that distance

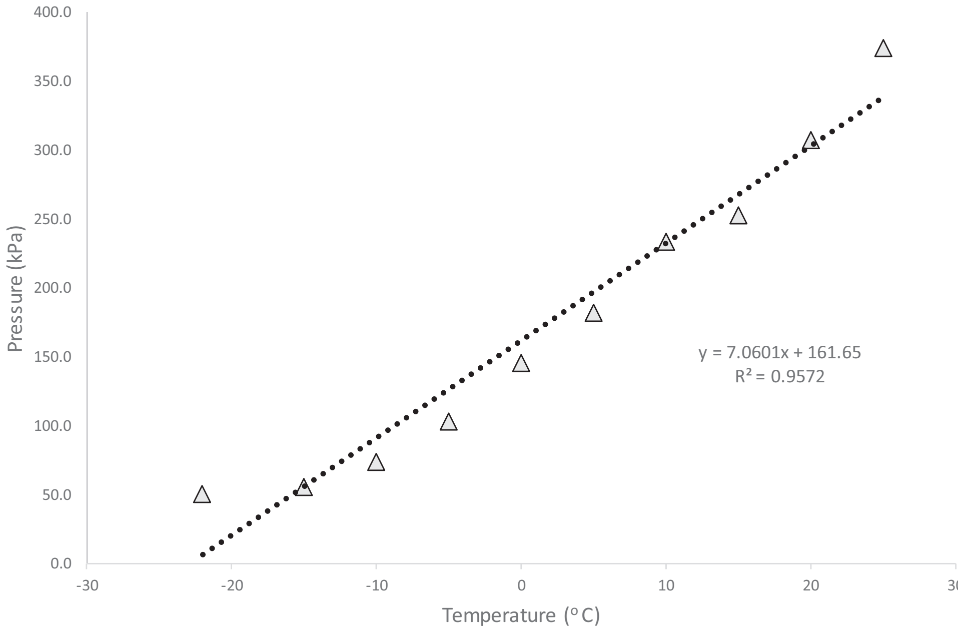

Figure 5. Relationship between canister temperature and head pressure of inert spray canisters filled with R134a propellant.

even as wind speed increased. Across all wind speeds tested, similar curves resulted with cross-winds in that the distance was reduced from 8 m to 3.5 m, with even the slightest cross-wind, but leveled off at 3.0 m as the wind speed increased. In the tailwind simulation, even a slight wind (0.5 m/sec) pushed the spray plume beyond the 10 m mark, outside of the simulation area, as did higher velocity tailwinds.

Repeated Releases

We tested 6 new cans of inert bear spray (UDAP 225 g) and 3 new cans of actual bear spray (Counter Assault™ 225 g) to document the decline in head pressure with successive releases of their content. The head pressure for unused inert cans was, on average, 1.5 times greater than for unused actual spray cans (530 kilopascals and 350 kilopascals, respectively), but depletion rates for both followed a logarithmic decline curve (Fig. 10). It required >100 pressurizations of the apparatus to exhaust cans. Decline in pressure was rapid from the onset, leveling off as canister head pressure approached zero (Fig. 10). Though varying for each of the actual bear spray cans, the average trigger-to-depletion was 128 depressions of the trigger. Because these cans were charged with 225 g of OC, carrier, and propellant,

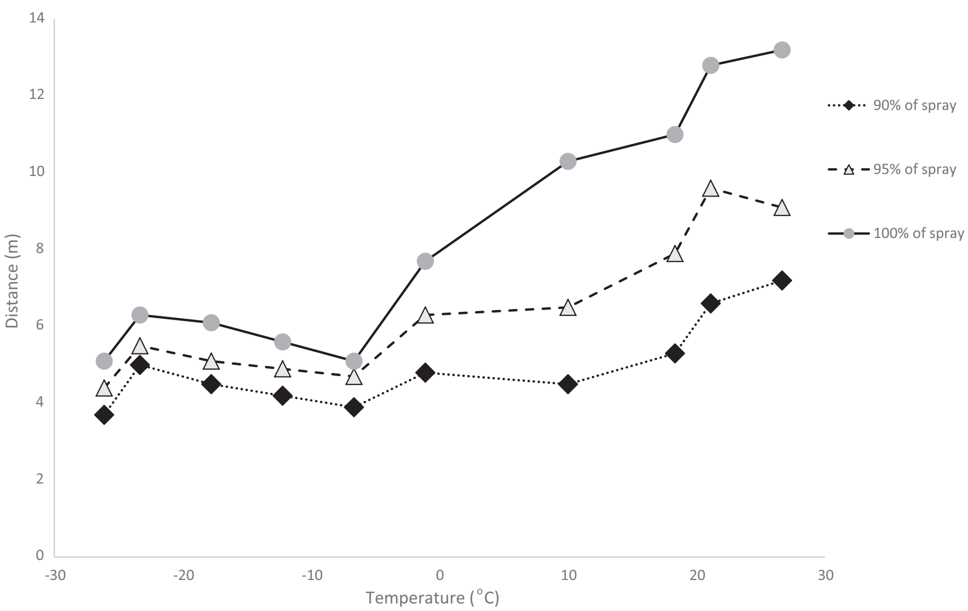

Figure 6. Bear spray plume distance as a function of temperature. Lines connecting measurements are to link symbols and do not indicate measurements between.

Figure 7. Spray plume dispersion as a function of temperature. The left image is of bear spray chilled to −23°C, the center image is of bear spray chilled to −17°C, and the right image is of bear spray at 18°C.

the average loss per trigger would have been 1.8 g/trigger (225 g/128 trigger events), but depletion was not linear. For example, half of the can's pressure (200 kilopascals) is depleted with the first 15 depressions of the trigger, or 10% of trigger depressions released 50% of the pressure and product (Fig. 10).

Time

We used 4 bear spray products (e.g., Counter Assault™ 230 g and 290 g cans; UDAP 225 g and 260 g cans) to explore the effect of time on spray performance (Fig. 11). Thirty-one unused cans of Counter Assault's 225 g product showed that on average cans lost 1.9 g (slope of regressed data)/year. We weighed 12 cans of Counter Assault's 290 g bear spray and on average this product lost 5.5 g/year. We weighed 22 unused cans of UDAP Pepper Power 225 g product and those cans lost an average of 0.7 g/year. Finally, 16 unused cans of Pepper Power 260 g bear spray lost an average of 0.6 g/year of propellant.

We measured the head pressures for 34 unused cans of Counter Assault™ (225-g canisters) bear spray of varying expiration dates (range = 2008–2015). We found no relationship ($R^2 = 0.001$) between canister weight and head pressure (Fig. 12), which seemed surprising given the

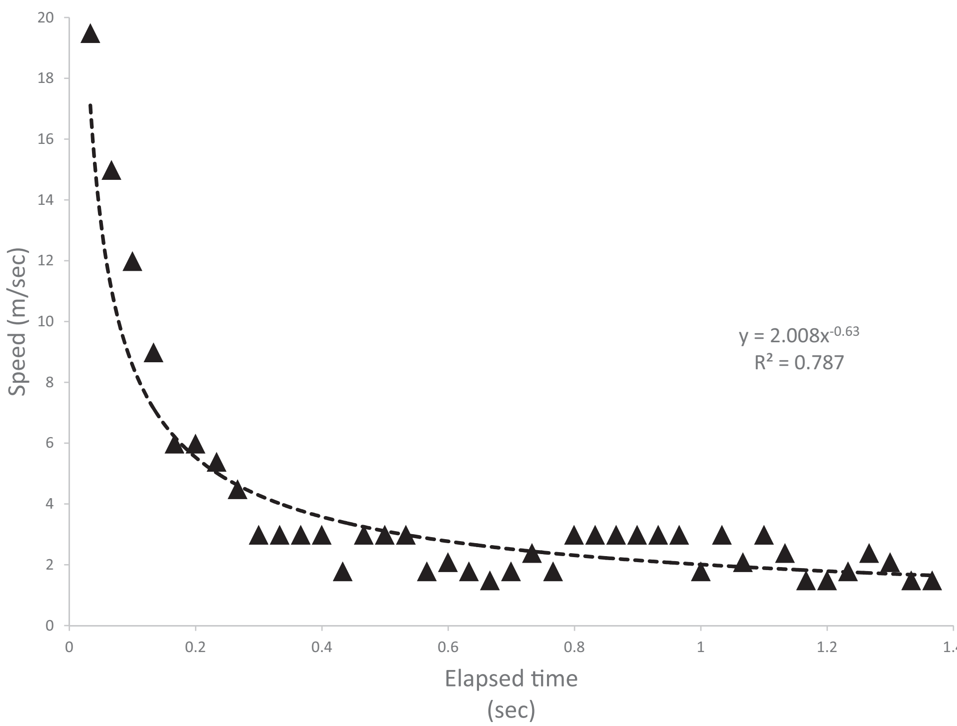

Figure 8. Change in bear spray speed (m/sec) over time (sec).

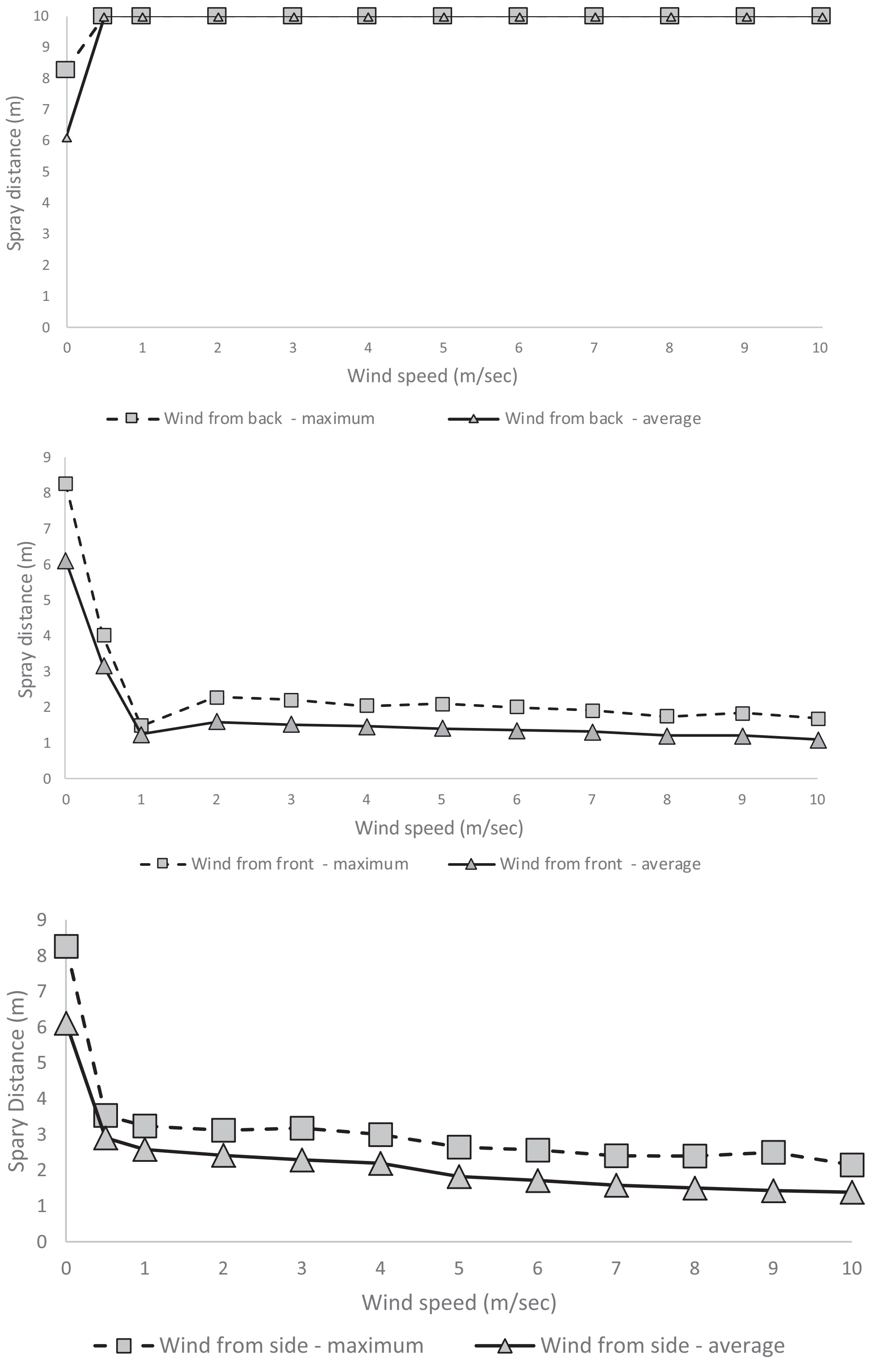

Figure 9. Simulated wind effects on bear spray plume reach (m). Top graphic depicts plume performance into a headwind, middle graphic depicts plume performance into a tailwind, and the bottom graphic depicts plume performance with a cross-wind. Lines connecting measurements are to link symbols and do not indicate measurements between.

moderate correlation ($R^2 = 0.494$) between canister age and weight.

DISCUSSION

Once triggered, a can of bear spray loses half its head pressure in the first 1.4 seconds (Fig. 10) and completely exhausts in 7 seconds (Counter Assault 2020). The loss of pressure, and hence spray plume distance, is rapid from the onset and is nearly exhausted only 4 seconds into continually spraying the can. Chilling cans of bear spray has a pronounced negative linear effect on canister head pressure, which, in turn, influences how far the spray plume extends.

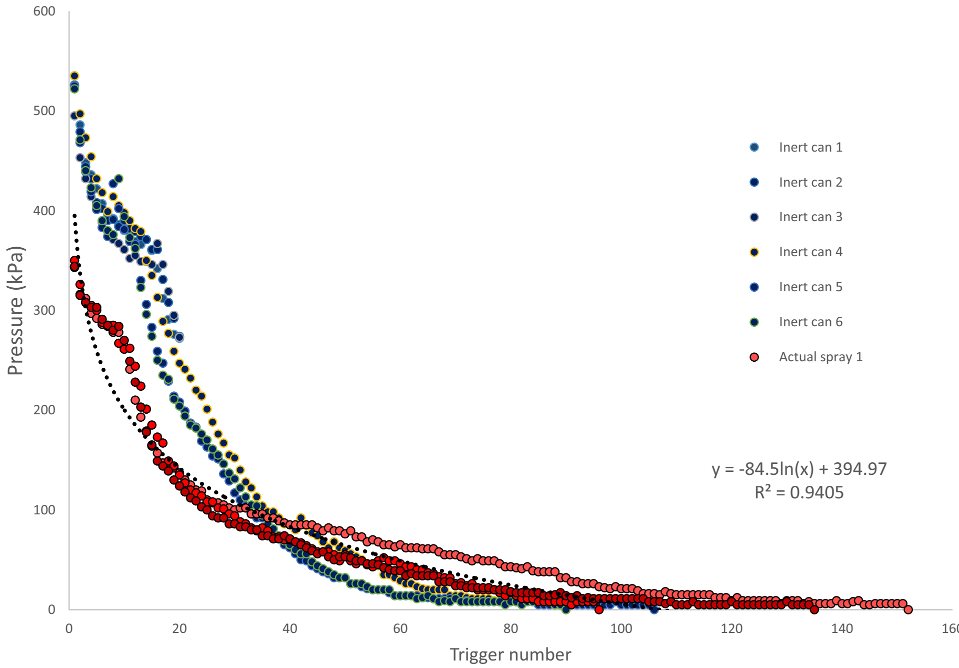

Figure 10. The decline in head pressure in inert and actual bear spray (Counter Assault™) canisters with successive releases until empty (kilopascals = 0).

Linear regression of distance versus temperature data predicted that for every 10°C drop in canister temperature, the plume loses 1–2 m of reach and becomes narrower and less diffuse. Although cold temperatures significantly reduce the reach and dispersion of bear spray, the user can still defend themselves (see −23°C photo in Fig. 7), though at close range (2 m). To mitigate this limitation, persons can carry bear spray beneath their coat where the warmth will keep pressures high and spray distance optimal. The trade-off, however, is that the user is less able to rapidly deploy the spray as when carried on the belt or pack strap. This finding also has implications for camping in cold weather and suggests keeping the canister inside your sleeping bag, rather than beside it, would keep the product warm and pressurized. Thus, temperature is a factor but, in our opinion, it can be surmounted by the user managing canister

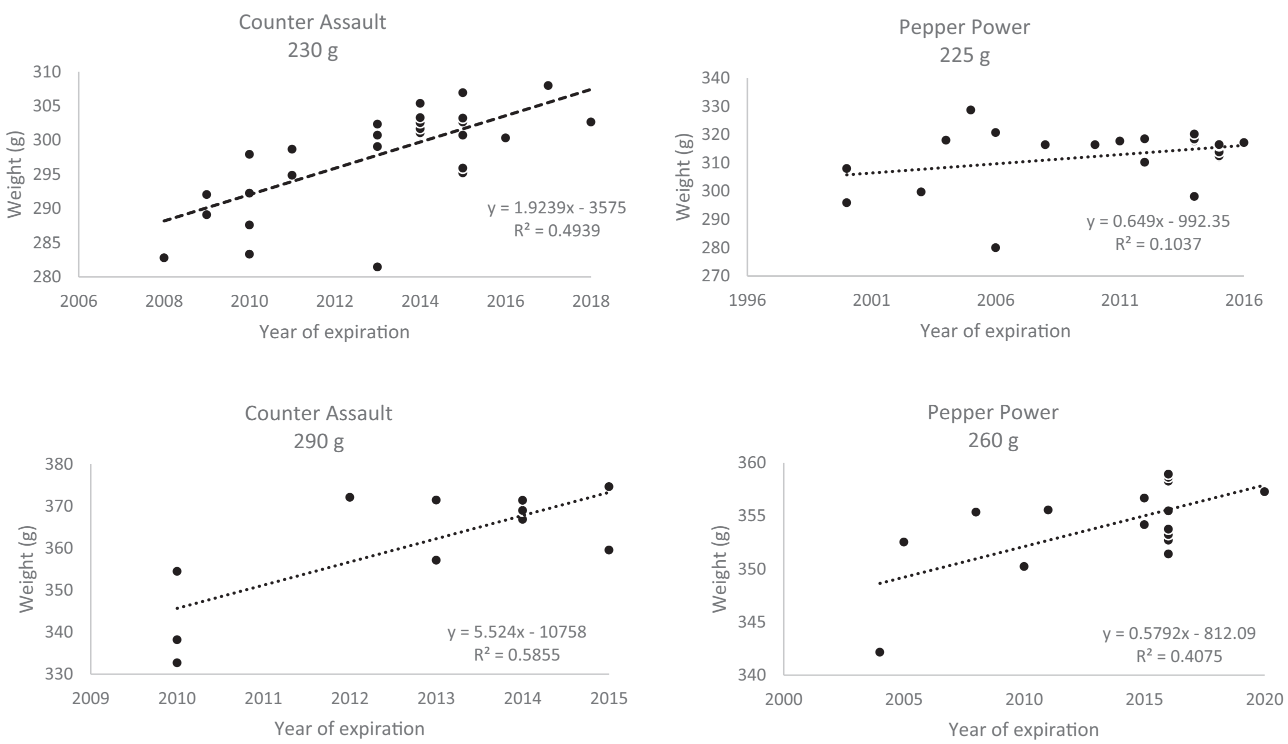

Figure 11. Weight of cans of unused bear spray by expiration date as printed on canisters.

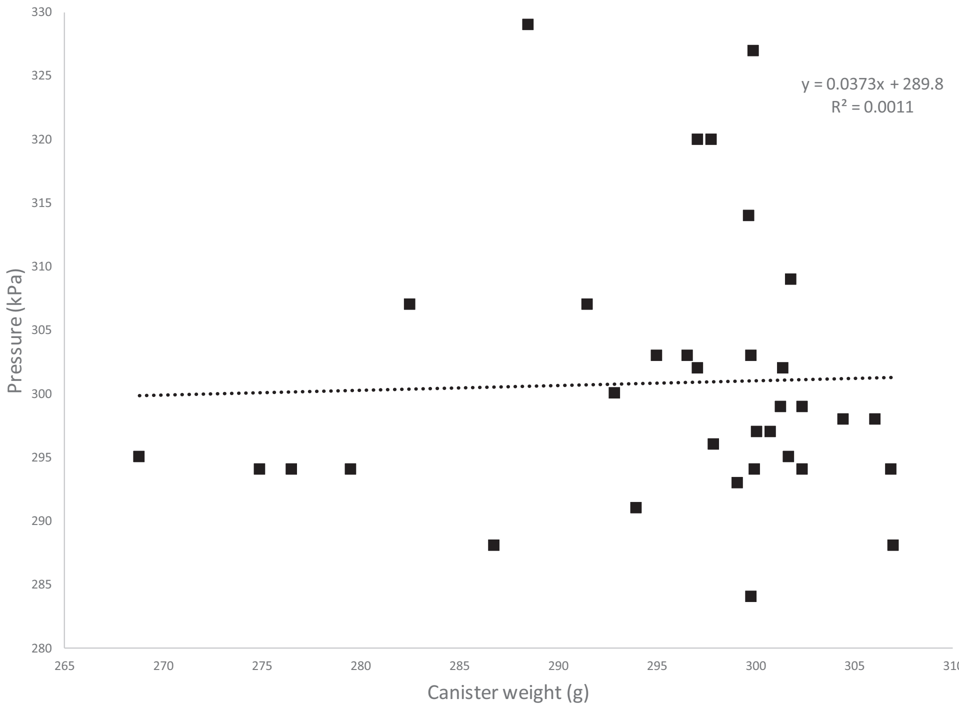

Figure 12. Relationship between canister weight and head pressure for 34 expired cans of 225-g Counter Assault™ bear spray product. Expiration dates ranged from 2008 to 2015.

temperature by keeping it in a warm place rather than letting cans of bear spray get cold.

Simulated headwinds reduced the distance spray can reach more than crosswinds and tailwinds extend it. We modeled plume behavior in winds only up to 10 m/second (~22 mph) for 2 reasons: the majority of North America human-bear conflict (brown and black bears) occur in relatively wind-protected areas (e.g., forests or scrublands) because visibility, which is poor in these environments, is a contributing factor to human-bear conflicts (Smith and Herrero 2018); and bears tend not to be moving about in high wind because it decreases their ability to smell and hear (Herrero 2002, Smith and Herrero 2018). In the Arctic, winds also create ground blizzards and in these conditions, polar bears may have visibility reduced in addition to smell and hearing. Our results indicate that even with strong headwinds, spray is ejected so forcefully (Fig. 9) that it can still reach 2 m directly in front of the person deploying it. Crosswinds have a similar, but less severe, effect on reach (Fig. 9) yet allow a person to spray the bear's face. Although not ideal, this is much better than having no deterrent option at all. Wind can also help by pushing the plume far beyond the advertised distance of 10 m for UDAP (2020), and 12 m for Counter Assault (2020). Wind is a factor in spray performance, but, in our opinion, given its unpredictability and the protection afforded by bear spray even under high wind scenarios, there is no reason to not carry it because of wind concerns.

The sequential de-pressurization of bear spray showed an initial steep loss of pressure followed by a much slower loss until all pressure was exhausted (Fig. 10). The relationship between trigger number and resulting head pressure was highly correlated ($R^2 = 0.94$) and logarithmic. The logarithmic regression equation that best fit these data can be used to predict the loss of head pressure and contents as a function of triggering. For example, assume a person has fired a 1-second burst of bear spray. Because a 225-g can of Counter Assault™ will spray for approximately 7 seconds, a 1-second burst (1/7 of the total spray time, or 1/7 of 128 triggerings = 18) can be used in the regression equation to show that 150 kilopascals remain after 1 second (44% of total pressure). The first second of spray released more of the contents than the remaining 6 seconds, and this suggests that test firing canisters quickly diminishes the ability of bear spray to protect the user. For this reason, we do not recommend test-firing bear spray. A person can weigh a can to make inferences about its residual pressure value as long as it is not expired (Fig. 10) because we found that expired cans were unpredictable in their pressure over time (Fig. 12). Test-firing not only quickly diminishes head pressure, and associated bear spray plume distance, but also leaves residue in the nozzle, which will ultimately end up on the user's skin, leading to intense burning. Additionally, as indicated by Smith (1998), bear spray residues may act as an attractant to bears so test-firing could have negative consequences if tested near campsites or other areas where humans concentrate. Both manufacturers of the products we tested recommended test spraying prior to initial use to verify pressurized contents and also recommended cleaning the nozzle assembly with soap and water (T. Lynch, UDAP general manager, personal communications).

The 4 bear spray products we tested all lost weight over time but at differing rates. Because the chemicals comprising bear spray are stable over time (P. D. Johnson, Counter Assault, personal communications), expiration dates are not based on chemical breakdown but on loss of propellant. We cannot explain the different loss rates between brands tested (UDAP™ and Counter Assault™) but suspect it may be due to a difference in components used in the head assemblies. Manufacturers recommend discarding cans ≥4 years old. Our research shows that at 4 years roughly 7–8% of propellant will have escaped (Fig. 11). This loss corresponds to a 40% reduction in head pressure given pressure depletion curves (Fig. 10). Given these findings, the 4-year expiration date appears reasonable.

Clearly, this information will prove useful to bear safety trainers who educate others regarding safe conduct in bear country. Safety in bear country is a personal responsibility and which deterrent(s) one chooses to carry is a personal decision. Bear spray has out-performed firearms in aggressive encounters in North America (Smith et al. 2012), but individuals are not statistical averages. Persons proficient in the use of firearms, as compared to those who are not, have a decided advantage in an aggressive bear encounter. There have been, however, cases where a rescuer shot the attacking bear and injured, or killed, the victim being mauled. A man in Alaska, USA, lost his leg when the rifle shot that killed the attacking bear also traversed his leg, and in Montana, USA, a would-be rescuer's gunshot killed the mauling victim. Conversely, in nearly all instances of aggressive black, brown, and polar bear encounters, bear spray has proven to be an effective deterrent (Herrero and Higgins 1998, Smith et al. 2008). Additionally, bear spray has never killed a person or a bear. Even for those carrying firearms, bear spray may prove useful given its ready availability (can always be on the hip in a holster), rapid deployment, ease of use, and non-lethal effect. For this reason, we recommend that bear spray have a place in everyone's bear deterrence toolkit.

MANAGEMENT IMPLICATIONS

Our results suggest that bear spray can be relied upon for protection in all areas where bears occur, even if the environment is windy or cold. Our findings show that testing bear spray, even with short bursts, rapidly depletes head pressure, reduces the amount available, and leaves noxious residues on the nozzle, which ultimately find their way onto hands, face, and clothing. Therefore, we recommend not testing cans and carrying fully-charged, unexpired product when in bear country. Protecting bear spray from the cold will help maintain maximum distance and dispersion. It can be kept warm by wearing the bear spray holster under a coat or placing it in, or under, a sleeping bag when camping in cold weather. Being mindful of these factors that affect the efficacy of bear spray will enhance your safety in bear country.

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